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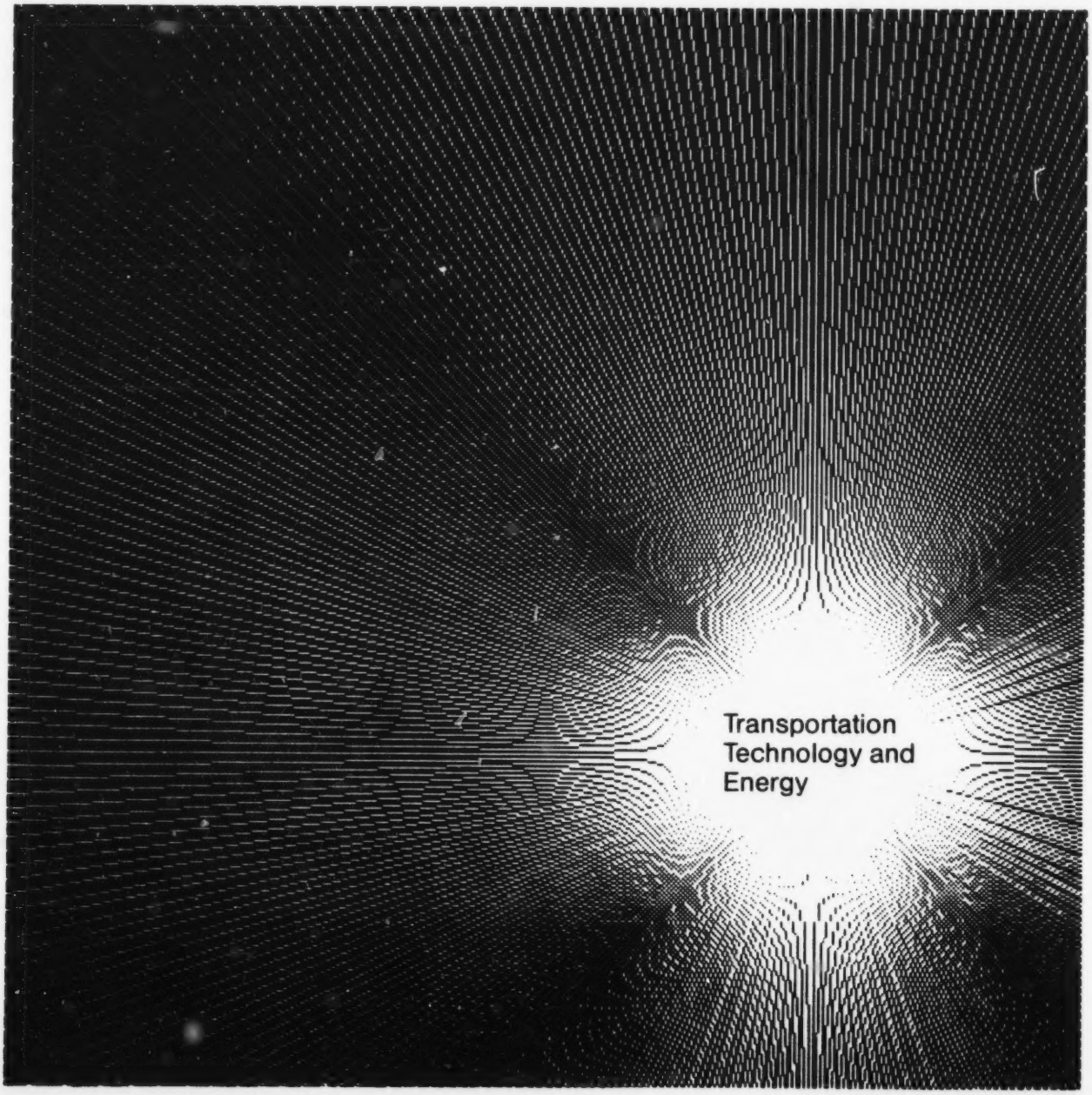
Comparative Stability and Handling Characteristics of an Eight-Axle Log-Haul Truck



Technical Report Documentation Page

MTC Report Number TT-CV-84-101	ISBN Number:	Other Document Number:	Date: April 1984

Title: Comparative Stability and Handling Characteristics of an Eight-Axle Log-Haul Truck

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Published by:
The Transportation Technology Office
Transportation Technology and Energy Branch, MTC

Client Group:

Participating Agencies:

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The results of the computer simulation are valid for the vehicle configurations under investigation, and should not necessarily be construed to be characteristic of all such vehicles.

Key Words: Boise Cascade, Tractor Trailer, B-Train, log-haul, turn, rollover, jackknife, simulation

Comments:

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TT-CV-84-101

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Published by:
Transportation Technology Office
Transportation Technology and Energy Branch
Ontario Ministry of Transportation and Communications
Hon. James W. Snow, Minister
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April 1984

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ABSTRACT

The stability and handling characteristics of an eight axle log-haul truck of innovative design, developed by Boise Cascade Canada Ltd., have been evaluated by computer simulation in comparison with others in use in the pulpwood haul industry. The Boise Cascade truck was not dissimilar to the other typical log-haul vehicles in turning and jackknife susceptibility. However, the Boise Cascade vehicle showed a tendency to rollover at lower speeds than the other three vehicles in entry to a steady turn at maximum legal load. The rollover tendency occurred at progressively lower speeds as the vehicle took on increased payloads.

The results of the computer simulation are valid for the vehicle configurations under investigation, and should not necessarily be construed to be characteristic of all such vehicles.

1/ INTRODUCTION

An eight-axle log-haul truck of innovative design has been developed by Boise Cascade Canada Ltd. in association with Kenworth Canada, Alcan, and Superior Trailers of Thunder Bay. The vehicle is shown in Figures 1 and 2. The vehicle consists of a long wheelbase four-axle tractor, with twin steer axles, and a dromedary assembly to carry load. The load consists of 2.6 m long pulp logs, loaded transversely. The semi-trailer has a triaxle with a load equalizing suspension and an air-lift axle. The vehicle was designed to the maximum dimensions and axle loads permitted by the Highway Traffic Act. As a consequence, it could generate a gross weight considerably in excess of the 63 500 kg (139 700 lb) maximum allowed by the Act.

The vehicle developers claimed a number of safety advantages for this vehicle over other conventional log-hauler trucks. Some of these were simply a reflection of the vehicle configuration, while others were clearly a result of deliberate choices made during the design stage. While safety was a stated consideration, it is also evident that the desired gross weight capability of this vehicle would make it a productive and fuel-efficient unit. Boise Cascade Canada Ltd., the user, therefore applied to Ontario Ministry of Transportation and Communications for a special overweight permit to operate the vehicle for a period of one year at a gross weight in excess of that allowable under the Highway Traffic Act. This permit was granted, at a gross weight of 70 000 kg (154 000 lb) with operations limited to an area of Northwestern Ontario where the low probability of simultaneous presence of another loaded truck would be very unlikely to threaten the structural integrity of bridges.

The vehicle has operated for nearly a year and its owner has now requested an indefinite extension of the permit. The lack of accidents involving the prototype vehicle over a one-year period was considered unlikely to indicate the accident potential of a fleet of those vehicles because the prototype had probably not encountered an extreme condition where an accident would have resulted. A more thorough investigation of the vehicle was therefore considered desirable because granting of a permit for an extended period of time would probably lead to a proliferation of

vehicles of this configuration. This report presents the findings on the stability and handling characteristics of the subject vehicle, as part of the investigation.

The claim that the subject vehicle is safer than other log-haul configurations can be evaluated by a comparison of that vehicle with others widely used in the pulpwood industry. Therefore, the vehicles selected for comparison were:

1/ the subject vehicle
   a/ unladen at a gross weight of 38 681 lb,
   b/ at a legal gross weight of 139 107 lb,
   c/ at the permitted gross weight of 153 663 lb, and
   d/ modified with a single front axle at a legal gross weight of 136 620 lb;

2/ a seven-axle two-trailer B-train at a legal gross weight of 131 927 lb (configuration 3S2S2);

3/ a seven axle tractor-trailer at a legal gross weight of 128 189 lb (configuration 3S4); and

4/ a five-axle tractor - trailer at a legal gross weight of 92 894 lb (configuration 3S2).

These vehicles are described in the next section. The comparison was based upon three operating conditions for all vehicles:

1/ vehicles making turns;

2/ loaded vehicles entering a curve on a high friction surface, when the expected mode of instability would be vehicle rollover;

3/ empty vehicles making a steady turn on a low friction surface, when the expected mode of instability would be tractor jackknife or trailer swing.

These comparisons were conducted by computer simulation using the assumptions on vehicle characteristics defined in the next section. The results are presented in Section 3.

Additional technical considerations relating to the analysis are discussed briefly in Section 4.

2/ VEHICLE CHARACTERISTICS

2.1/ Boise Cascade Log-Hauler

This vehicle is shown in Figures 1, 2 and 2(a), and is described in Table 1. It is composed of a four-axle Kenworth tractor with dual steer axles. The extended chassis houses a dromedary load frame behind the cab and is coupled with an aluminum trailer manufactured by Superior Trailers of Thunder Bay. The vehicle was examined in four basic configurations,

1/ empty, 38 681 lb;
2/ legally loaded @ 139 107 lb; and
3/ as permitted @ 153 663 lb; and
4/ modified with a single steer axle at a legal gross weight of 136 620 lb.

The connection between tractor and trailer is a standard "fifth wheel" providing rotation about the yaw and pitch axes. Axle 5 is an air-lift axle that was considered lifted for empty simulations. This vehicle is equipped with Michelin radial tires all around and operated with a two-stage front suspension and equalizing triple rear axle set. It has been operating for one year in Northern Ontario under special permit. Data on this vehicle was obtained from its manufacturer, supplemented with data obtained directly from component suppliers and other data on file at MTC.

2.2/ B-Train (3S2S2)

This hypothetical vehicle is of standard design taken from the Ministry inspection records. It is comprised of a tractor with two trailers interconnected with a standard B-train connection. The load was cross stacked 2.6 m logs, similar in density to the load on the other trucks. Bias ply ribbed tires are used throughout the vehicle. The vehicle is shown in Figure 4 and is described in Table 1. It was examined under maximum allowable load conditions of 131 927 lb.

2.3/ 7 Axle Tractor Trailer (3S4)

This hypothetical vehicle is a standard tractor with a 45' trailer dimensionally similar to that used in 2.1 but with a steel chassis. The trailer is loaded with 2.6 m cross stacked logs. It is shown in Figure 3 and described in Table 1. It was examined under a near maximum load condition of 128 189 lb.

2.4/ 5 Axle Tractor Trailer (3S2)

This hypothetical vehicle is a standard tractor with a 45' semi-trailer. The trailer is loaded with 2.6 m cross stacked logs. The tires were bias ply ribbed all around. The truck and trailer are equipped with typical suspensions for this type of vehicle. The vehicle is shown in Figure 5 and is described in Table 1. It was examined loaded to 92 985 lb and also empty.

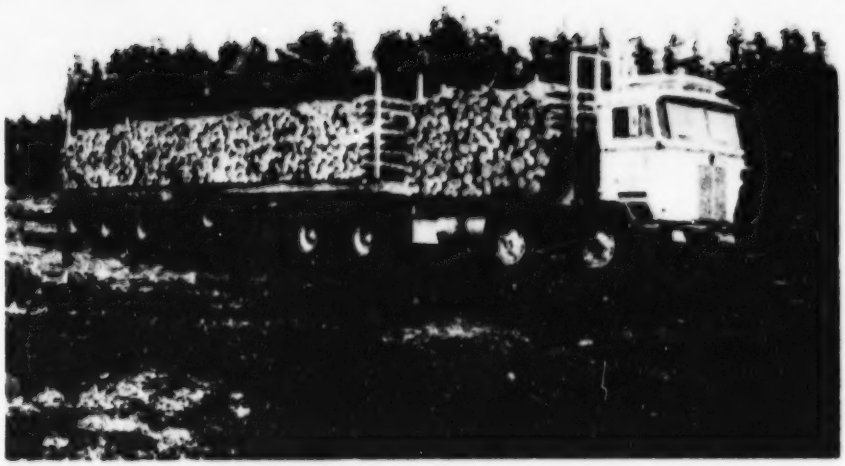


Figure 1/ Boise-Cascade Log Hauler

LOAD/DIMENSION DATA

AXLE LOADS

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	CONFIGURATION
7,642	7,642	4,833	4,833	—	4,577	4,577	4,577	1. EMPTY 38,681 lb.
16,878	16,878	18,427	18,427	19,393	16,368	16,368	16,368	2. 139,107 lb.
17,923	17,923	20,581	20,581	22,000	18,218	18,218	18,218	3. 153,663 lb.

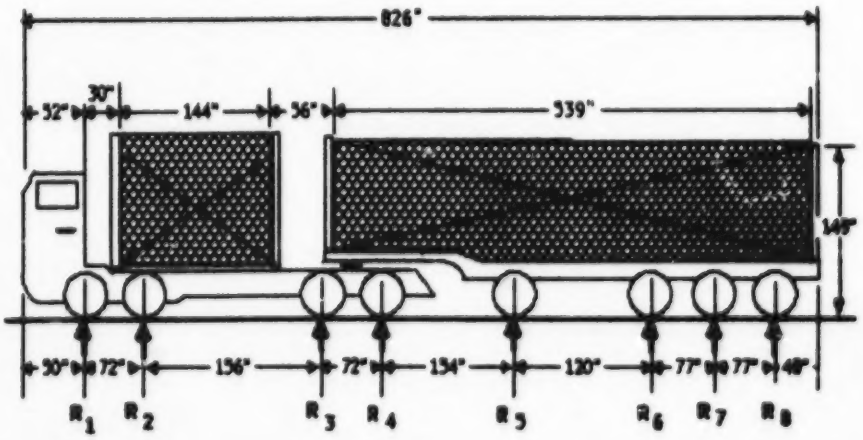


Figure 2/ Boise-Cascade Log Hauler

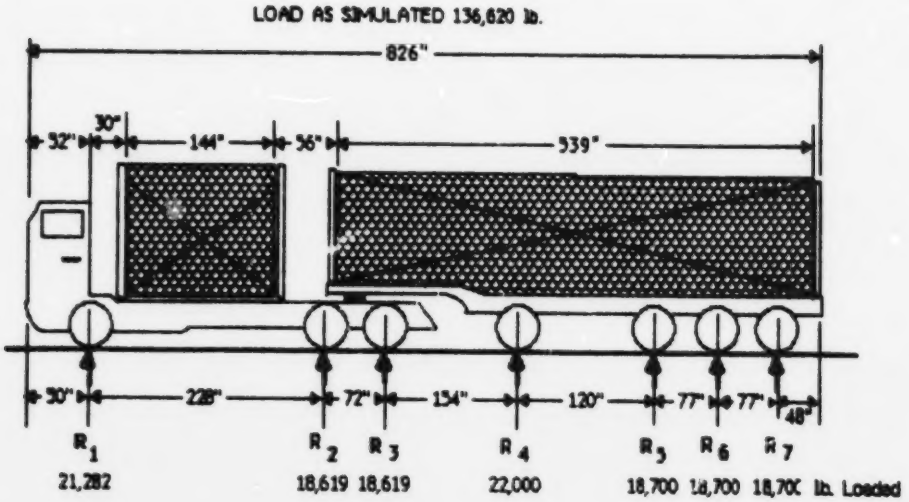


Figure 2a/ Boise Cascade Log Hauler Modified with Single Front Axle

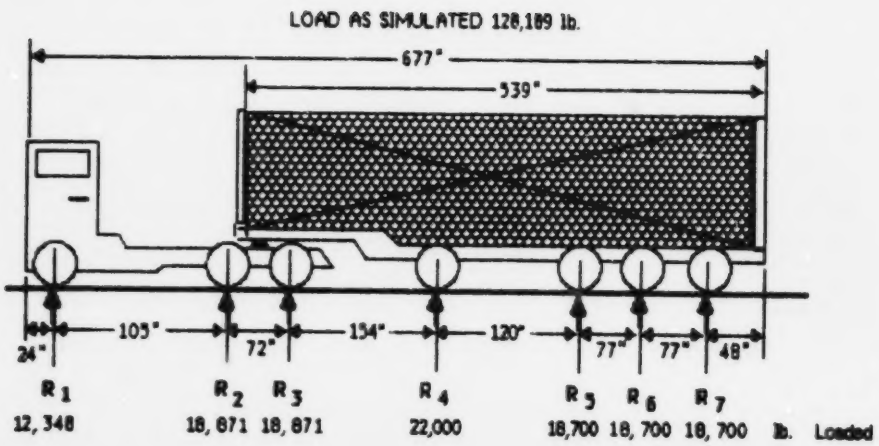


Figure 3/ 7 Axle Tractor Trailer (3S4)

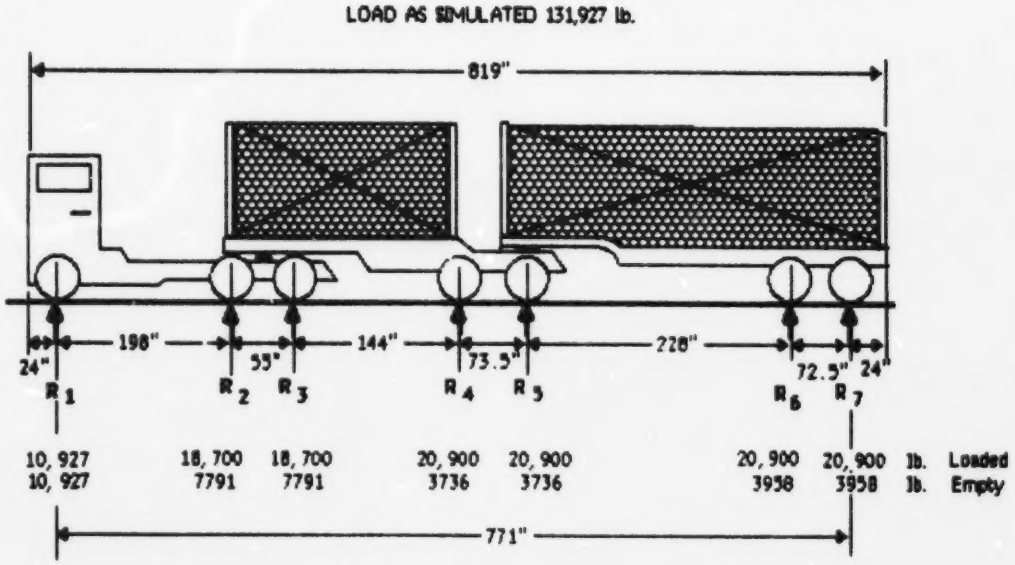


Figure 4/ 3S2S2 B-Train Log Hauler (Typical)

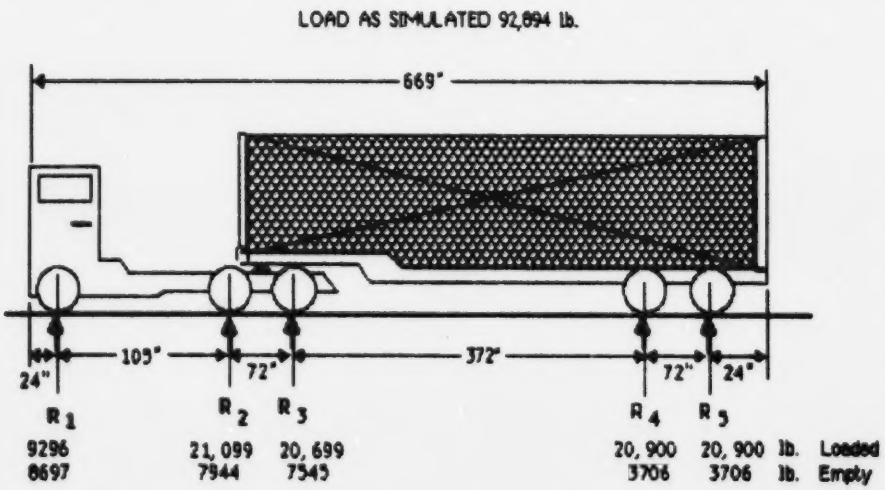


Figure 5/ 5 Axle Tractor Trailer (3S2)

Table 1/ Log-Hauler Technical Data

Title	# Axles/Weight (lb)/#Units	Unit	Axle/Load (lb)	CG Height (Inches)	Overall Height (In.)
Boise Cascade as Built	7 38 681 2	1	1 7 642 2 7 642 3 4 833 4 4 833	40.00	N/A
		2	5 4 577 6 4 577 7 4 577	38.00	N/A
Boise Cascade as Built	8 139 107 2	1	1 16 878 2 16 878 3 18 427 4 18 427	79.55	142
		2	5 19 393 6 16 368 7 16 368 8 16 368	94.15	136
Boise Cascade as Built	8 153 663 2	1	1 17 923 2 17 924 3 20 581 4 20 581	85.40	155
		2	5 22 000 6 18 218 7 18 218 8 18 218	99.95	147
Boise Cascade Single Front Axle	7 136 620 2	1	1 21 282 2 18 619 3 18 619	61.32	102
		2	4 22 000 5 18 700 6 18 700 7 18 700	99.50	146
Tractor Trailer 3S4	7 128 189 2	1	1 12 348 2 18 871 3 18 870	40.00	N/A
		2	4 22 000 5 18 700 6 18 700 7 18 700	97.45	163
B Train 3S2S2	7 131 927 3	1	1 10 927 2 18 700 3 18 700	40.00	N/A
		2	4 20 900 5 20 900	79.72	155
		3	6 20 900 7 20 900	81.70	152
Tractor Trailer 3S2	5 92 894 2	1	1 9 296 2 21 099 3 20 699	40.00	N/A
			4 20 900 5 20 900	71.57	111

3/ PERFORMANCE COMPARISONS

3.1/ Turning

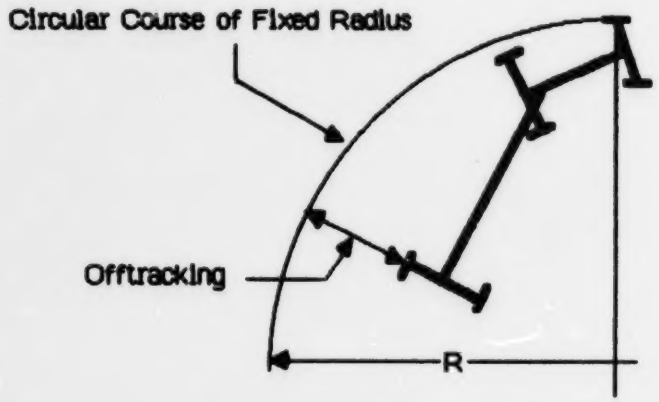
Offtracking is the radial distance that the path of the rear wheels deviate from that of the front wheels when the steer axle is driven in a circular path of fixed radius. Figure 6 shows the offtracking of the three vehicles at steady state in a long turn for various turn radii. The results show that with the Boise Cascade between the two, the tractor trailer has the greatest and the B-train the least offtracking.

When an articulated vehicle makes a right-hand turn of small radius, the driver must make a complex steer manoeuvre such that the rear axle of the vehicle tracks closely around the curve. This often results in intrusion of the vehicle into traffic lanes other than its own. The swept path in such a right turn is quite different than that due to offtracking. The three vehicles were evaluated using a 90° right-hand turn of 52.5 ft (16 m) curb radius. Their swept paths are shown on Figure 7 together with measures of intrusions and clearances. As can be seen from Figure 6, all vehicles encroached into the oncoming lane between two-thirds to one full lane width over a distance of about 100 ft. The empty and loaded Boise Cascade vehicle bracketed the tractor trailer and the B-train turned slightly inside the other two vehicles.

The turning performance of Boise Cascade vehicle is not regarded as significantly different than that of a tractor trailer with a 45' semi-trailer. Both require somewhat more space to turn than a B-train because of the additional articulation of the double trailer.

3.2/ Rollover

In order to evaluate the high speed rollover response of the Boise Cascade log-hauler configuration, a computer simulation was performed to compare the response of the Boise Cascade log-hauler with that of other conventional log-haulers, namely; the tractor trailers (3S2, 3S4) and B-train, on a high friction surface.



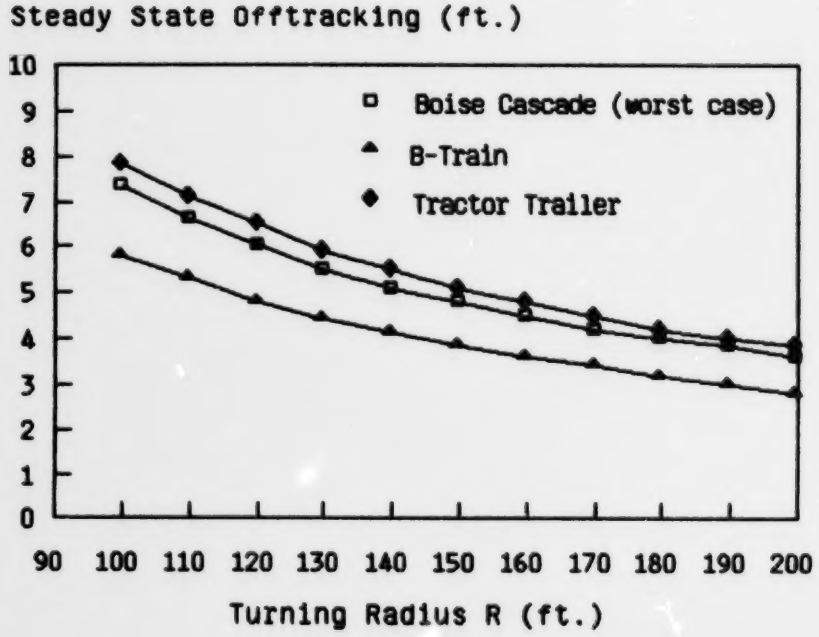
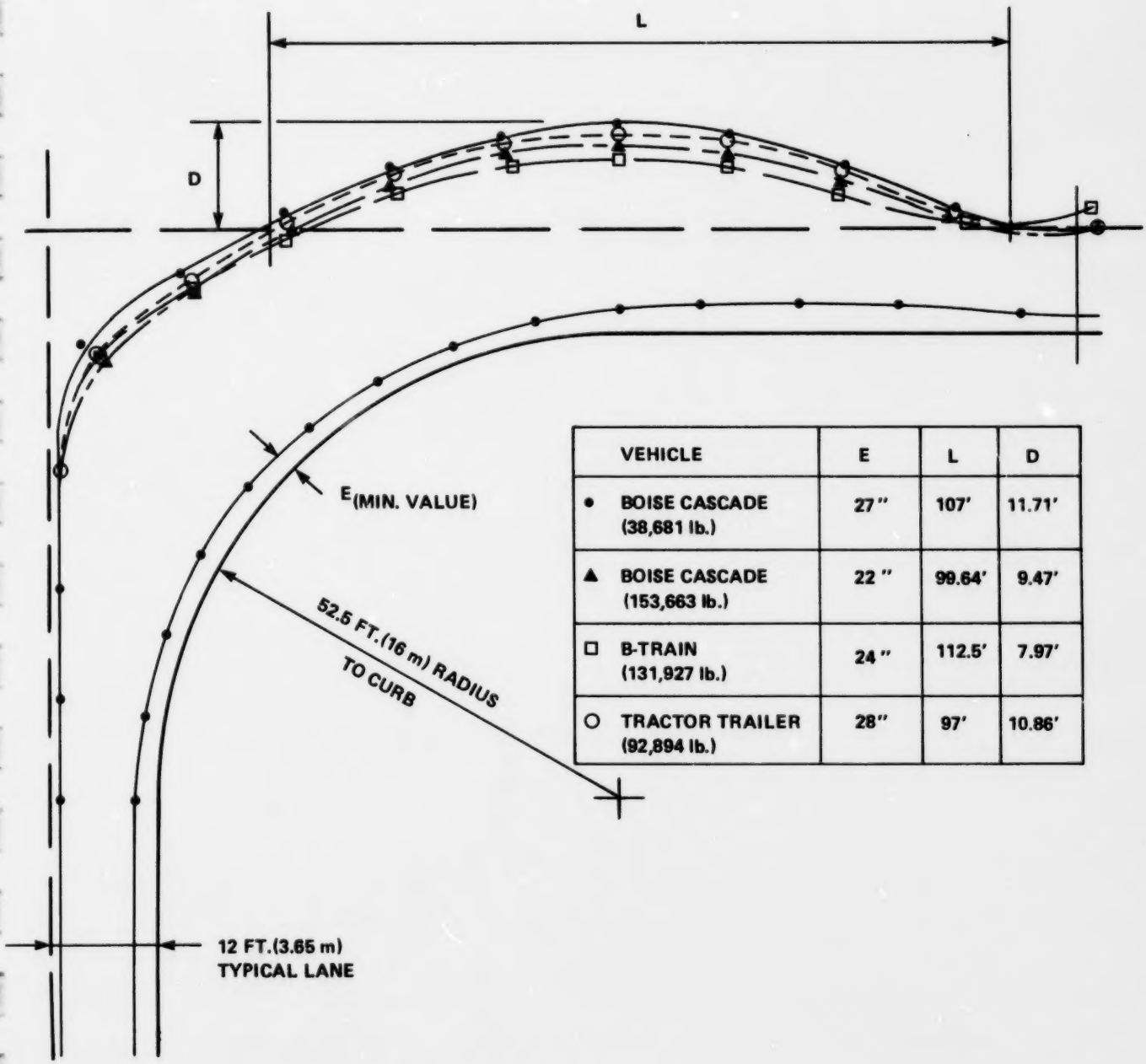


Figure 6/ Steady State Turning Response



	VEHICLE	E	L	D
•	BOISE CASCADE (38,681 lb.)	27"	107'	11.71'
▲	BOISE CASCADE (153,663 lb.)	22"	99.64'	9.47'
□	B-TRAIN (131,927 lb.)	24"	112.5'	7.97'
○	TRACTOR TRAILER (92,894 lb.)	28"	97'	10.86'

Figure 7/ Sweep Characteristics in 52.5 ft.(16 m) Radius Right Turn

The computer program employed in this analysis was the Yaw/Roll program developed at the University of Michigan Transportation Research Institute (UMTRI) [1]. By incorporating the "state-of-the-art" simulation techniques in the computer model, the program provides a useful tool in studying the dynamic roll and yaw motion of heavy commercial vehicles under high speed manoeuvre. It was necessary to make a minor modification to the program to represent the twin steer axle of the Boise Cascade vehicle.

A total of six log-haulers were compared in this analysis:

1/ Boise Cascade	- 153 663 lb
2/ Boise Cascade	- 139 107 lb
3/ Boise Cascade with single Front Axle	- 136 620 lb
4/ B-train	- 131 927 lb
5/ 5 Axle Tractor trailer	- 92 984 lb
6/ 7 Axle Tractor with 45' Trailer	- 128 189 lb

They were compared by means of entry to a typical highway curve, taken from the geometry of a curve on Highway 105 just north of the Wabigoon River bridge. It consisted of a 125' long spiral, and a 1510' long 9° circular curve. The radius of the circular curve is approximately 636 ft. The curve is posted with the advisory speed of 54.7 ft/sec (60 kph). In the simulation, the 8% superelevation of the curve was ignored for simplicity, to be accounted for later in the analysis. Figure 8 shows the schematic of the curve.

The vehicle was "steered" to track the prescribed path by selecting the "driver" option in the computer model. Two parameters were necessary to define the "driver", the lag time and preview time. These two parameters were adjusted within the program to keep the vehicle close to the desired path. Once the values were chosen, the same values were used throughout the simulation for all vehicles. The speed was increased for each vehicle until the vehicle became unstable. The "driver" model successfully followed the curve, within a lane, for all vehicles at all speeds.

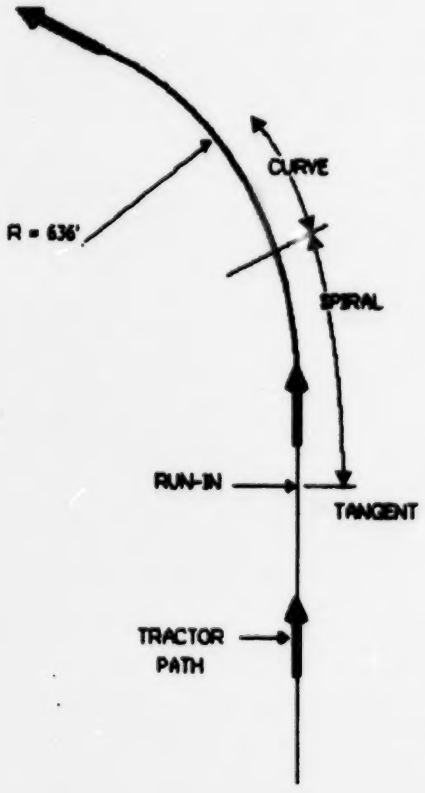


Figure 8/ High Speed Trajectory

Results of the simulation indicated that the mode of instability associated with a laden log-hauler on a high friction surface was predominantly trailer rollover.

In this analysis, a vehicle unit was considered to be unstable and rolled over when its roll angle exceeded 7° during a high speed manoeuvre. It is generally felt that a roll angle higher than 7° will be sufficient to cause a wheel lift at high speed. Once wheel lift has occurred, the simulation may no longer predict vehicle response accurately. Ensuing motion may result in rollover, trailer slide, or even recovery. However, wheel lift to this point, even if it does not result in rollover, is sufficiently undesirable that the simulation should be terminated.

Figure 9 shows the rollover threshold speed of the log-haulers with respect to peak tractor lateral acceleration. It is observed that the Boise Cascade configurations have the lowest rollover threshold. With the permit load at 153 663 lb, the Boise Cascade vehicle was predicted to rollover at 59 ft/s (65 kph) whereas at the legal load, as built or modified with a single front axle, it rolled over at 63 ft/s (69 kph). The seven axle tractor trailer rolled over at 65 ft/s (71 kph). The five axle tractor trailer (3S2) had the highest rollover threshold at 79 ft/s (87 kph), and the B-train had an intermediate rollover threshold at 70 ft/s (77 kph). The dotted line in Figure 9 is the speed limit posted for the circular curve, adjusted down to remove the superelevation to make it comparable with the simulation.

The results show that at a legal load, the rollover threshold speed of the Boise Cascade vehicle is significantly less than that of the three other log-haulers considered for comparison. The rollover threshold speed of the Boise Cascade vehicle further decreased as its gross weight was increased to the permit load.

3.3/ Jackknife

Jackknife tendencies were evaluated by a linearized, steady state steering response analysis [2]. The analysis was conducted for the empty Boise Cascade and tractor trailer on a low friction surface such as a wet or slippery highway.

Articulated vehicle performance can be measured by any of several ratios or gains. Each gain is the ratio of vehicle response to driver input. Figure 10 shows tractor yaw velocity gain as a function of forward speed. A rapid increase in gain, or yaw velocity response per unit input is observed between 27 and 30 ft/s indicative to the approach of jackknife instability. The speed at which vehicle jackknife occurs is known as the critical speed. These are 31.8 ft/s and 33.9 ft/s for the tractor trailer and Boise Cascade respectively. The modest advantage of the Boise Cascade vehicle is not regarded as particularly significant because jackknife accidents tend to occur due to locking of tractor drive axles during severe braking rather than entry to a steady turn.

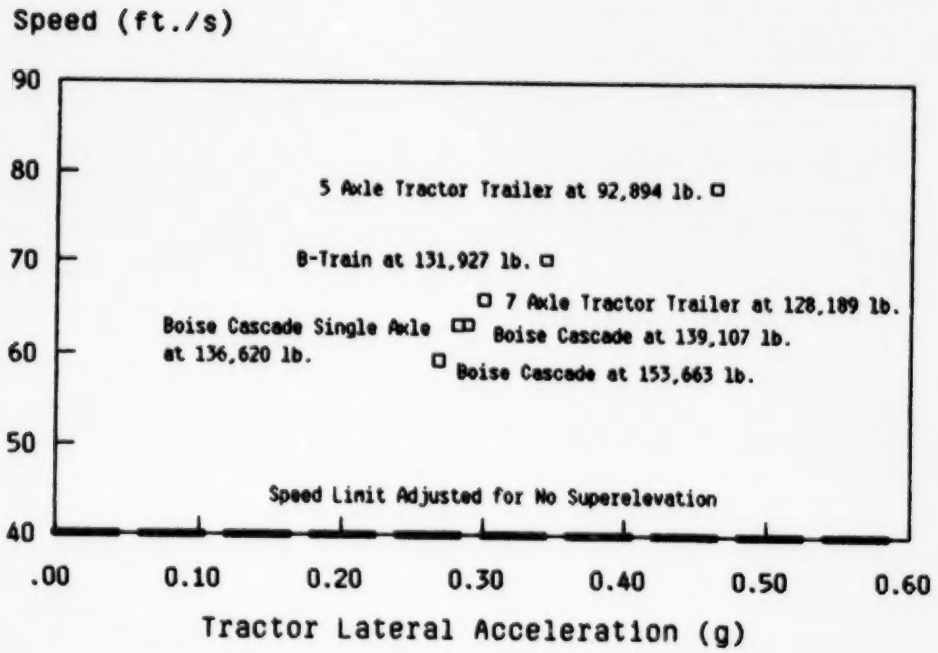


Figure 9/ Speed at Rollover for Circular Turn

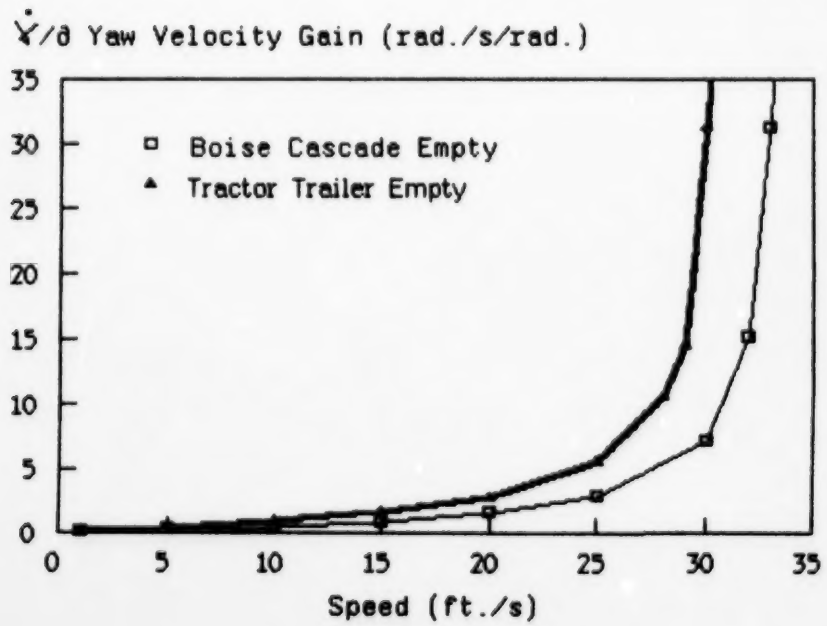


Figure 10/ Yaw Velocity Gain for Empty Boise Cascade and Tractor Trailer

4/ DISCUSSION

The performance comparisons presented in the previous section have been based upon various computer simulations and simplified analysis methods. While the absolute values might not necessarily be borne out in practice, the trends and ranking are in accordance with experience.

From the analysis of more than 2000 rollovers among 9000 accidents in the files of the Bureau of Motor Carrier Safety in the U.S. it has been found that the proportion of rollovers in single vehicle accidents increase sharply as the rollover threshold is decreased. This is illustrated in Figure 11 [3]. Figure 12 shows by computer simulation that the rollover threshold is strongly related to payload and centre of gravity heights [3]. The rollover limits demonstrated by tilt table tests confirm experimentally the correlation between rollover threshold and centre of gravity height [4]. Figure 13 also shows that there is a good correlation for vehicle roll between tilt tests and dynamic tests [5]. The rollover threshold is also reduced as the proportion of load carried by the tractor steer axles is increased [3].

While rollover in dynamic manoeuvres is very complicated, and is influenced by driver action, vehicle design, vehicle configuration, and load, nevertheless some useful insights can be gained by use of simple static considerations.

Log haul vehicles carry heavy loads and as a consequence the centre of gravity of the loaded vehicle becomes very high. Table 1 lists the centre of gravity heights of the vehicles examined here and Figure 14 shows that there is a strong relation between centre of gravity height and rollover threshold. Figure 15 compares the static roll moment for each of the vehicles studied with the rollover threshold. This is analogous to a tilt test. It is observed that the general form of Figures 14 and 15 are similar and this finding is in agreement with the general findings of other published data, as discussed above.

The designers of the Boise Cascade vehicle have evidently striven to improve its productivity and safety. They have correctly identified that centre of gravity height is an important factor as far as rollover is concerned.

However in reducing the loaded height of the vehicle the loaded length has been increased from 45 to 57 ft and a portion of that load has been placed on the tractor. Careful design of a lightweight trailer has resulted in increased trailer payload, which increases the payload height of the trailer. The loaded height of the Boise Cascade vehicle at the permit load of 153 662 lb is only 155" on the tractor, and 148" on the trailer, compared to 162" for the conventional 7 axle vehicle. The total vehicle static roll moment however is substantially greater because of the much greater loaded length and payload. This is seen in Figure 15. The lower rollover threshold from the simulation results is to be expected. The payload carried by the tractor also contributes to the reduction of roll threshold as noted above.

Removing the front axle from the Boise Cascade vehicle and reducing its load to the legal level of 136 620 lb results in a rollover threshold close to that of the 7 axle tractor trailer. It is however, our opinion that the rollover threshold of the conventional 7 axle tractor trailer as used in the pulp log haul industry is much lower than desirable, see Figure 11.

Ministry inspectors report that overloads and excessive speeds are frequently observed in the pulpwood haul industry. Both these factors reduce the margin available to the driver before rollover will occur. The inadequate load retention practice also reported may act as a safety valve, so that the load will spill rather than cause rollover of the vehicle, as would happen if the load were tightly secured to the trailer.

The improved rollover resistance of the B-Train is attributable to both its lower centre of gravity and six axles available to resist rollover. The Boise Cascade and seven axle tractor trailer vehicles discussed in this report have only five axles effective in resisting rollover. This is because the steer and air lift axles have very little roll stiffness. The five axle tractor trailer has a much lower centre of gravity height which results in a higher rollover threshold despite the fact that it has only four axles effective in roll.

Recent amendments to the Highway Traffic Act now permit 48 foot trailers and 75.46 ft (23 m) overall length. The configuration of the Boise Cascade vehicle evaluated here may no longer be the one preferred by its

designers in the light of these amendments. Detailed changes may be made to the suspensions of the Boise Cascade vehicle to improve its roll resistance capabilities. Such changes could also be made to other vehicles, hence their relative ranking would not change.

The study of vehicle dynamics is very complex and depends on many parameters not discussed in detail here. The aforementioned findings are for the specific vehicles under examination only and should not necessarily be applied to other vehicles.

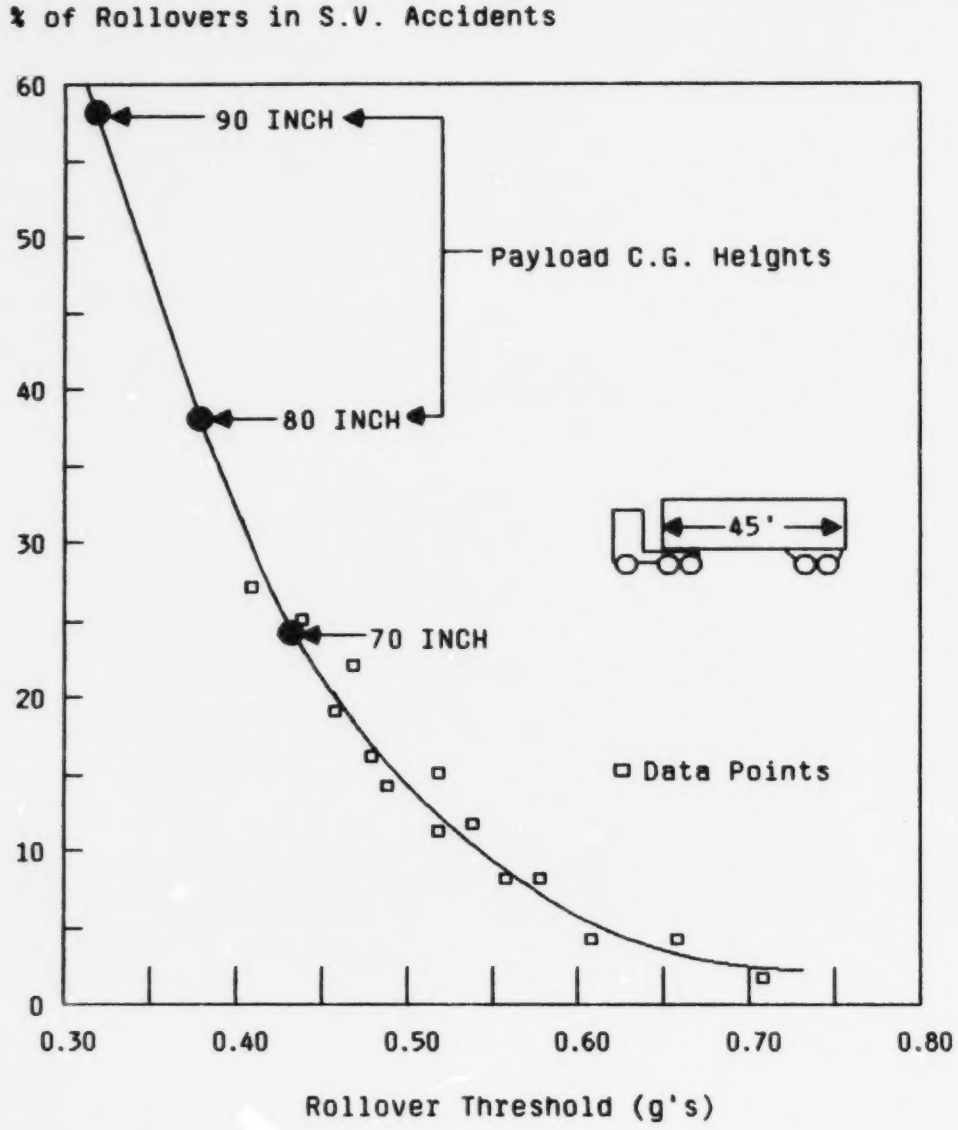


Figure 11/ Payload C.G. Height Variations vs Accident Data "from Reference 3 "

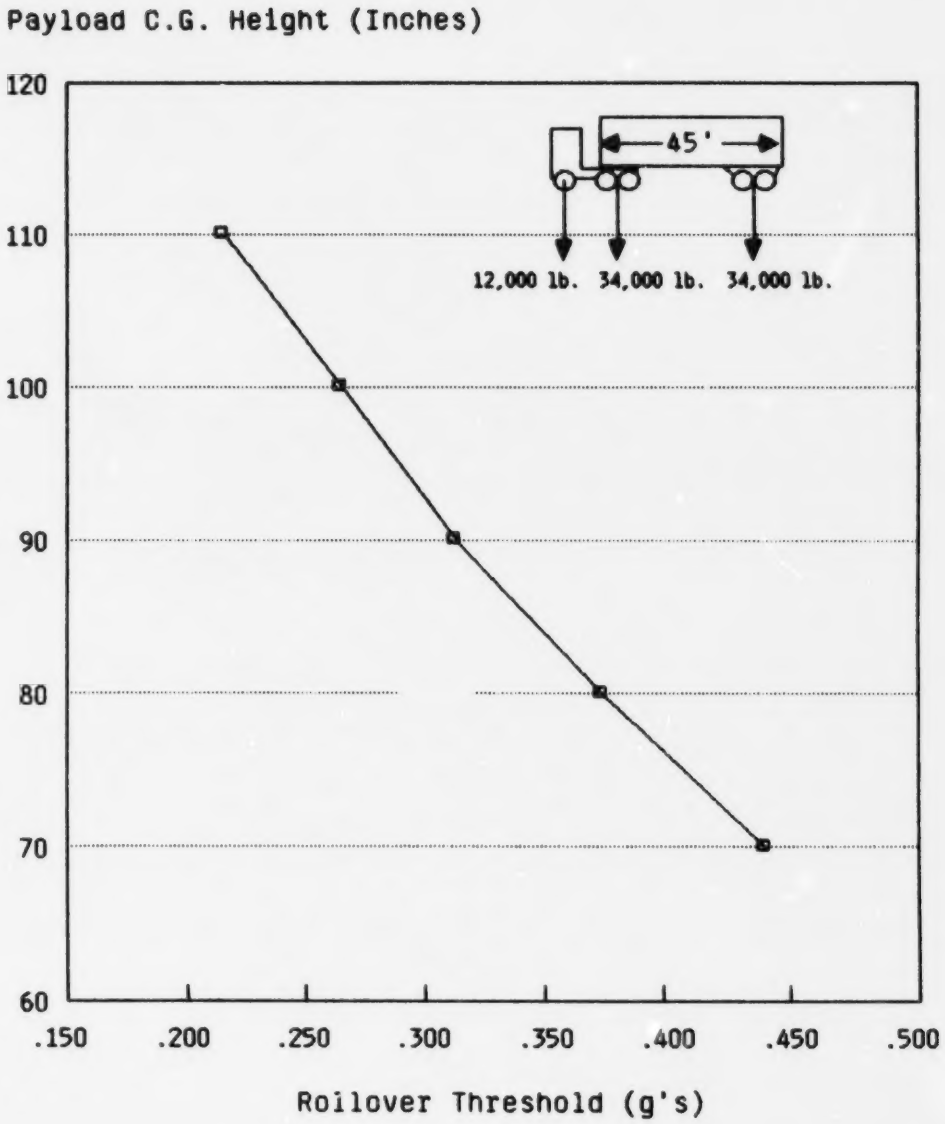
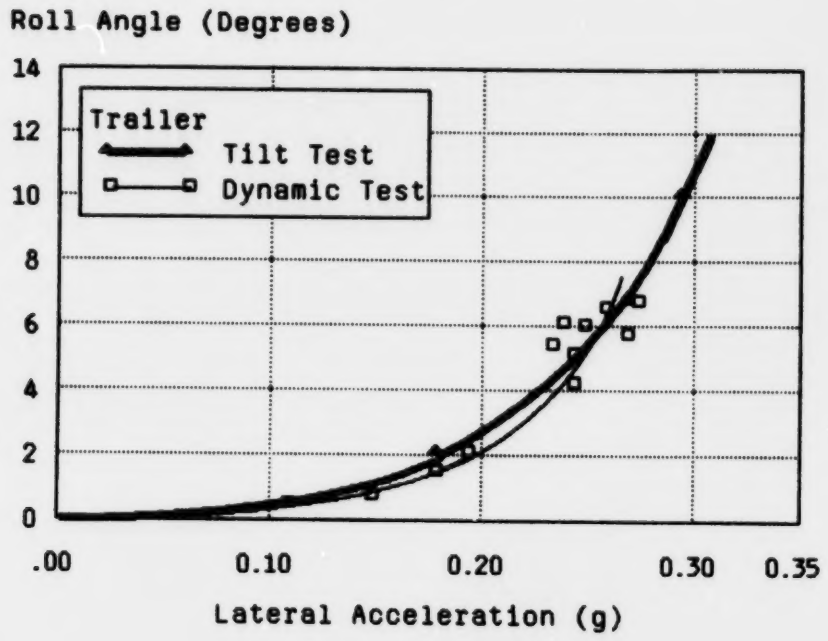
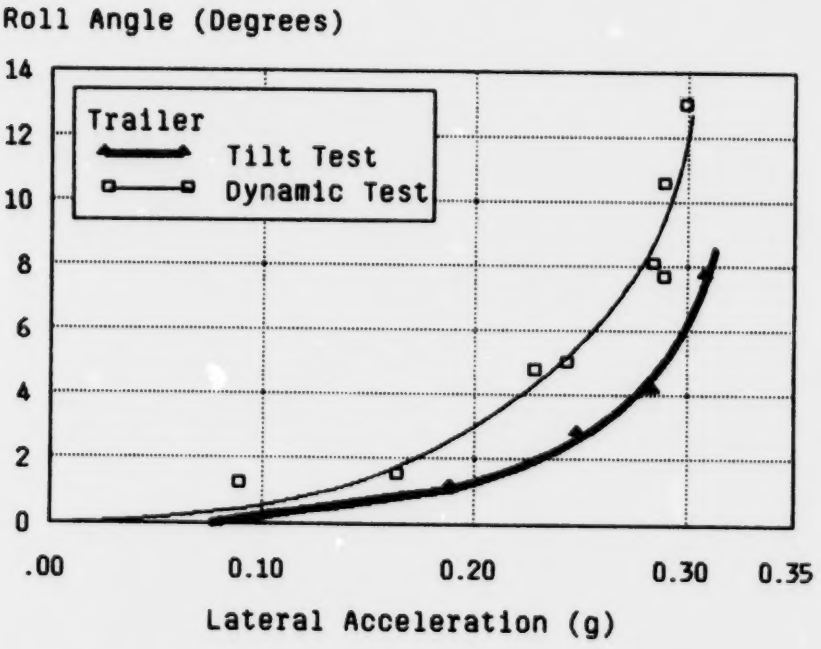


Figure 12/ Influence of Payload C.G. Height on Rollover Threshold "from Reference 3 "



Lateral Acceleration and Roll Angle of Tasker Standard Spring Base Trailer at 32 Tonnes



Lateral Acceleration and Roll of Tasker Wide Spring Base Trailer at 32 Tonnes

Figure 13/ Relationship Between Tilt Test and Dynamic Test Data "from Reference 5 "

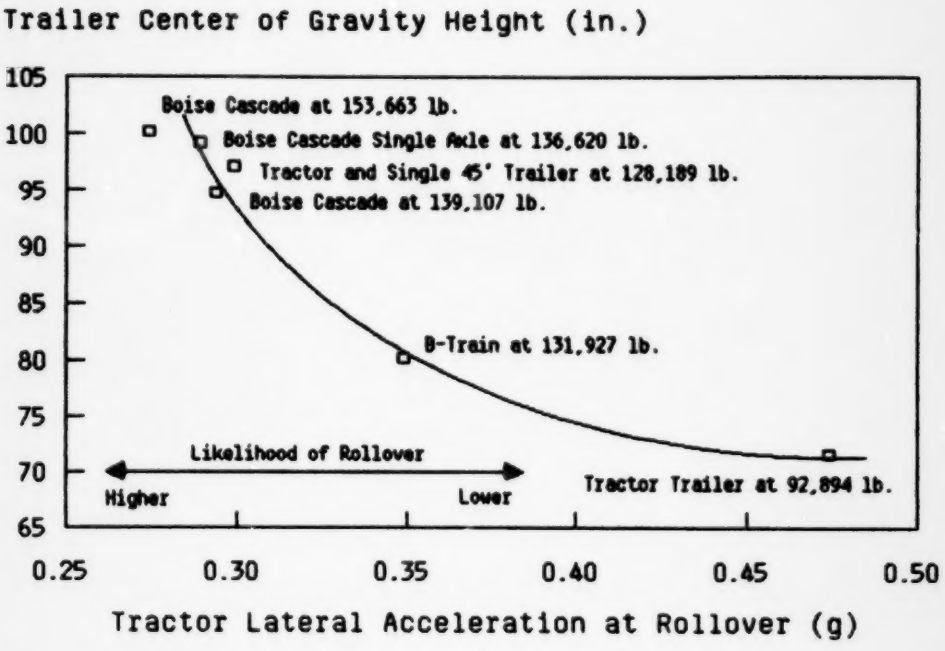


Figure 14/ Relationship Between Rollover Threshold and Trailer Center of Gravity Height

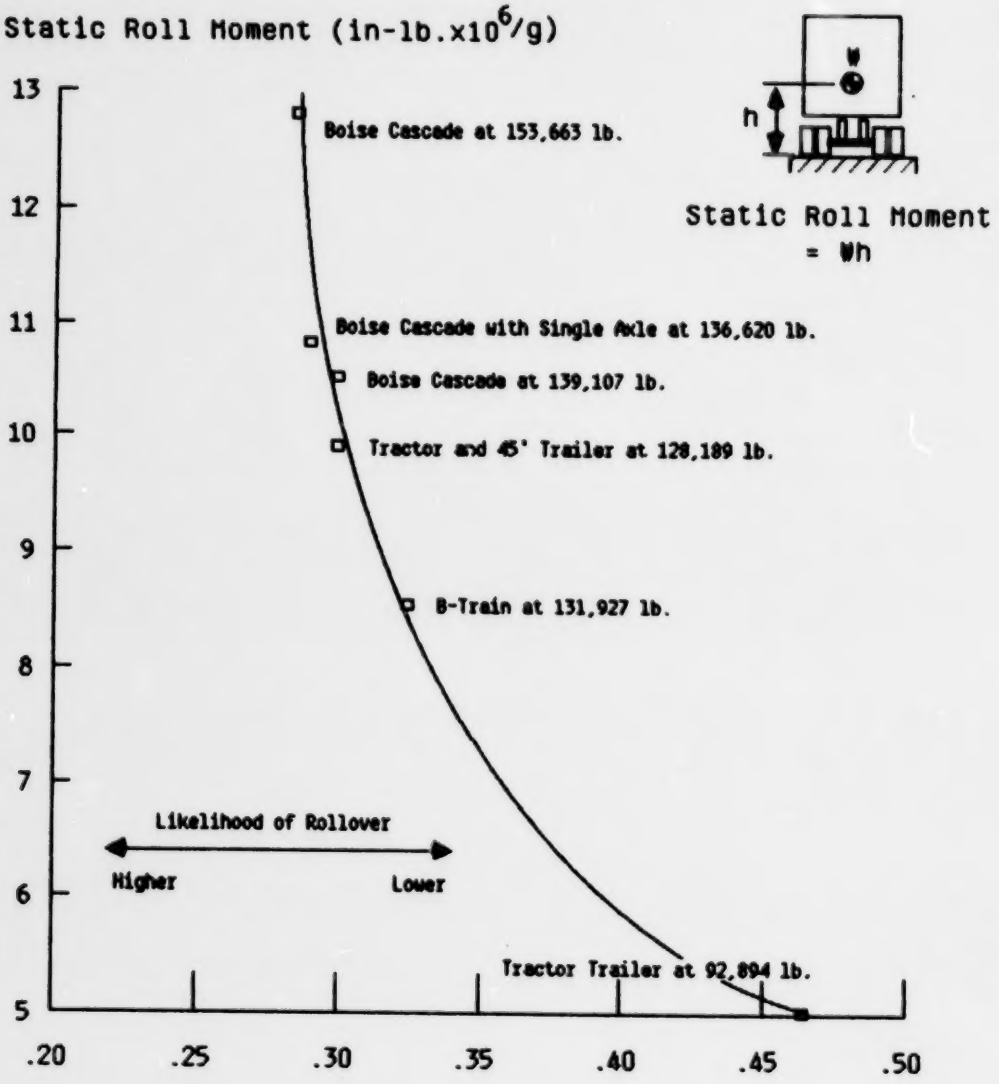


Figure 15/ Relationship Between Static Roll Moment and Lateral Acceleration to Cause Rollover

5/ CONCLUSIONS

The stability and handling characteristics of an eight-axle log-haul truck of innovative design developed by Boise Cascade Canada Ltd. have been evaluated in comparison with others in use in the pulpwood haul industry. The turning characteristics of the Boise Cascade vehicle differ little from the others evaluated. There is also no significant difference seen in jackknife tendencies. However, the results show that at a legal load, the rollover threshold speed of the Boise Cascade vehicle is not better than that of the other vehicles. The rollover threshold speed of the Boise Cascade vehicle is further reduced as its gross weight is increased to the special permit load of 154 000 lb (70 000 kg).

The reduced rollover margins of the Boise Cascade vehicle should be balanced carefully against economic and other benefits when the permit application is being considered. Proliferation of such vehicles may become a concern.

The low rollover threshold revealed by this study for some vehicles currently in use for log haul is also a matter for concern. At the present time no criterion for minimum rollover threshold exists.

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